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Seismic images and magnetic signature of the Late Jurassic to Early Cretaceous Africa–Eurasia plate boundary off SW Iberia

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SUMMARY

Over the last two decades numerous studies have investigated the structure of the west Iberia continental margin, a non-volcanic margin characterized by a broad continent–ocean transition (COT). However, the nature and structure of the crust of the segment of the margin off SW Iberia is still poorly understood, because of sparse geophysical and geological data coverage. Here we present a 275-km-long multichannel seismic reflection (MCS) profile, line AR01, acquired in E–W direction across the Horseshoe Abyssal Plain, to partially fill the gap of information along the SW Iberia margin. Line AR01 runs across the inferred plate boundary between the Iberian and the African plates during the opening of the Central Atlantic ocean. The boundary separates crust formed during or soon after continental rifting of the SW Iberian margin from normal seafloor spreading oceanic crust of the Central Atlantic ocean. Line AR01 has been processed and pre-stack depth migrated to show the tectonic structure of the crust across the palaeo plate boundary. This boundary is characterized by a 30–40-km-wide zone of large basements highs related to landward-dipping reflections, which penetrate to depths of 13–15 km, and it marks a change in the character of the basement structure and relief from east to west. In this study, we have used pre-stack depth migrated images, the velocity model of line AR01 and magnetic data available in the area to show that the change in basement structure occurs across the fossil plate boundary, separating African oceanic crust of the M series (M21–M16) to the west from the transitional crust of the Iberian margin to the east.

Key words: continental margins, Horseshoe Abyssal Plain, magnetic anomalies, oceanic crust, plate tectonics, seismic reflection.

1 INTRODUCTION

1.1 Tectonic setting

Approximately 175 Ma ago seafloor spreading started in the Central Atlantic ocean with continental break-up between Africa and North America (Klitgord & Schouten 1986). The relative motion of Africa in respect to Europe was accommodated by a strike-slip fault located approximately along the present day Azores–Gibraltar line (AGL in Fig. 1). Seafloor spreading between Iberia and North America was initiated slightly north of the current AGL and later propagated northward, although the age of the first seafloor spreading magnetic anomalies M11 and M3 is not well-constrained, especially within the Tagus Abyssal Plain (Pinheiro *et al.* 1992; Srivastava *et al.* 2000). Between M0 and approximately Chron 34 (84 Ma), (Kent & Gradstein 1986, geological timescale), Iberia was behaving as an independent plate, while Africa changed its motion towards a northeasterly directed compression (Dewey *et al.* 1989, Fig. 2). Slightly before Chron 34, Iberia started moving together with Africa and the plate boundary between Africa and Eurasia jumped from the AGL to the north, at the Bay of Biscay (Srivastava *et al.* 1990a,b; Roest & Srivastava 1991). However, the location of the Late Jurassic–Early Cretaceous boundary between the rifting SW Iberian margin and the oceanic spreading of the Central Atlantic has been poorly defined, both because kinematics of the Iberian Plate are still under debate and because mapped magnetic anomalies have been generally considered inadequate to settle this question. This area is commonly known in literature as the Azores–Gibraltar Fracture Zone (AGFZ in Figs 2 and 3). The southwestern margin of the Iberian Peninsula endured complex tectonics since Mesozoic time, encompassing several rift phases from Late Triassic to Cenomanian–Albian times. Opening of the North Atlantic added further stretching in the area (Terrinha 1998). It is still unclear how and where a transform system connected the Tethys

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†Deceased (2003 January).

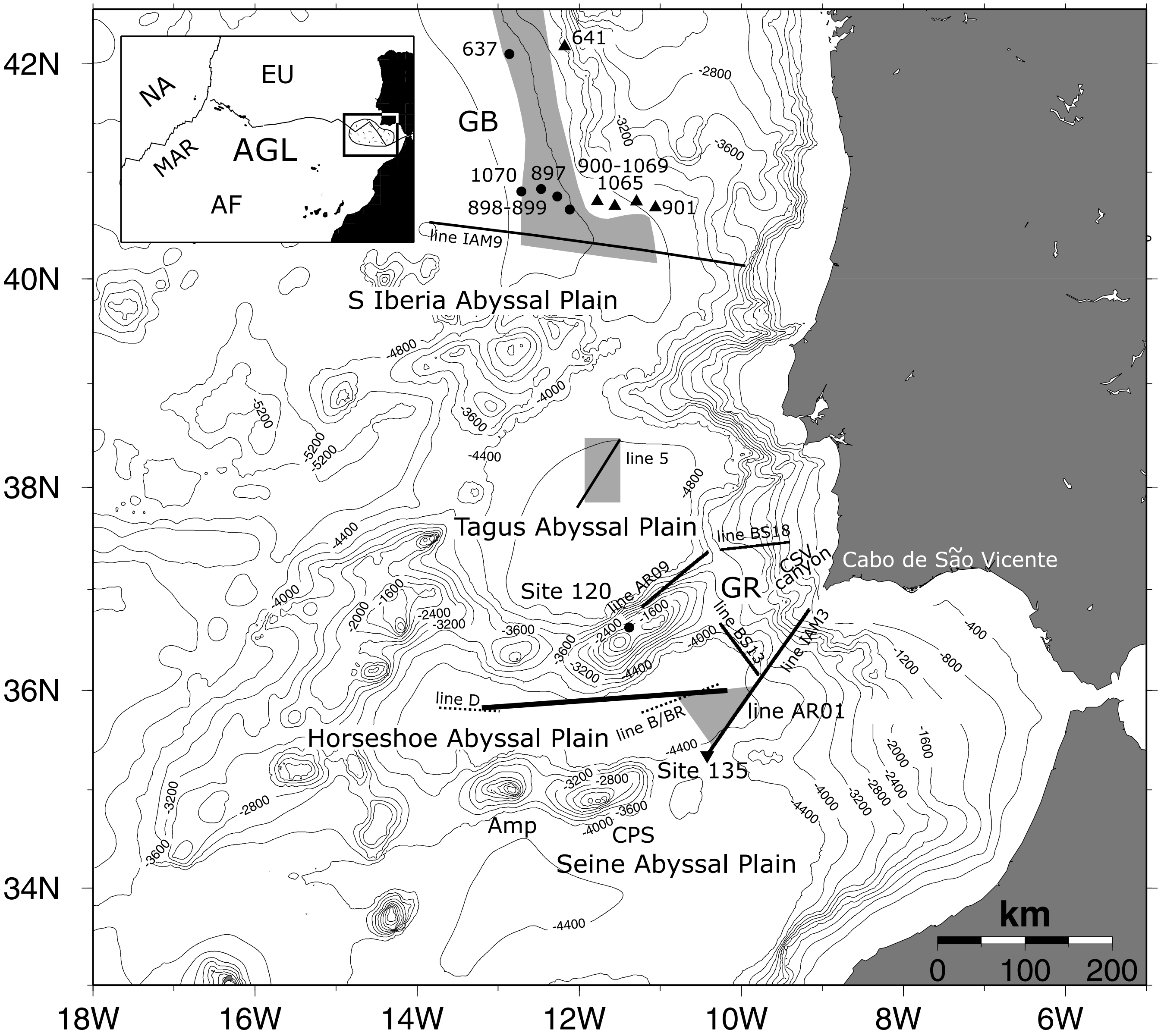

Figure 1. Bathymetry of the oceanic area offshore the west Iberia Atlantic margin. Bathymetry contours are at 400-m intervals (data from GEBCO97 Digital Atlas web site: `www.nbi.ac.uk`). Solid lines shows AR01 and the seismic profiles mentioned in the text. Dotted lines D and B/BR indicate refraction lines acquired by Purdy (1975). The ODP sites are represented as symbols, filled circles show where peridotites were sampled or drilled, triangles where lower continental crust, thinned continental crust and continental shelf environment were sampled. DSDP site 135 is represented as an inverted triangle. Shaded areas represent the COT extent in Dean *et al.* (2000) on line IAM9; Pinheiro *et al.* (1992) on line 5; Tortella *et al.* (1997) on line IAM3 and this paper on line AR01. Inset shows a general sketch of the area with the present-day plate boundaries between Africa, Eurasia and North America (`http://www.gsj.go.jp/dMG/dMGold/free/plates/Intro.html`, compiled by NOAA Global Relief Data on CD-ROM 93-MGG-01), with a stippled-patch area to indicate the diffuse plate boundary zone. Eurasian Plate (EU); African Plate (AF); North American Plate (NA); Mid Atlantic Ridge (MAR); Azores-Gibraltar Line (AGL); Galicia Bank (GB); Gorringe Ridge (GR); Ampère Seamount (Amp); Coral Patch Seamount (CPS); Cabo de São Vicente canyon (CSV).

ocean to the Central Atlantic, allowing oceanization in this area to form the neo-Tethys during the Late Jurassic–Early Cretaceous. Unfortunately, on available MCS profiles (Sartori *et al.* 1994; Zitellini *et al.* 2004), the Mesozoic tectonic setting has been strongly reworked by the Cenozoic reactivation, so that major evidence of a hypothetical fossil transform zone is not detectable on seismic images. During Aquitanian–Burdigalian, after a long-lasting convergent regime, a collisional event between the south Iberian and the north African continental margins started (Flinch 1993). During the Miocene the frontal part of the Gibraltar Arc underwent compression with the emplacement of an accretionary wedge and the gravitational discharge of the chaotic body spread in the area west of the Strait of Gibraltar (Torelli *et al.* 1997).

1.2 State of the art

During the past two decades, a great number of investigations have been carried out off the NW Iberia margin: diving cruises, Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) drilling, dredging and geophysical surveys, recently

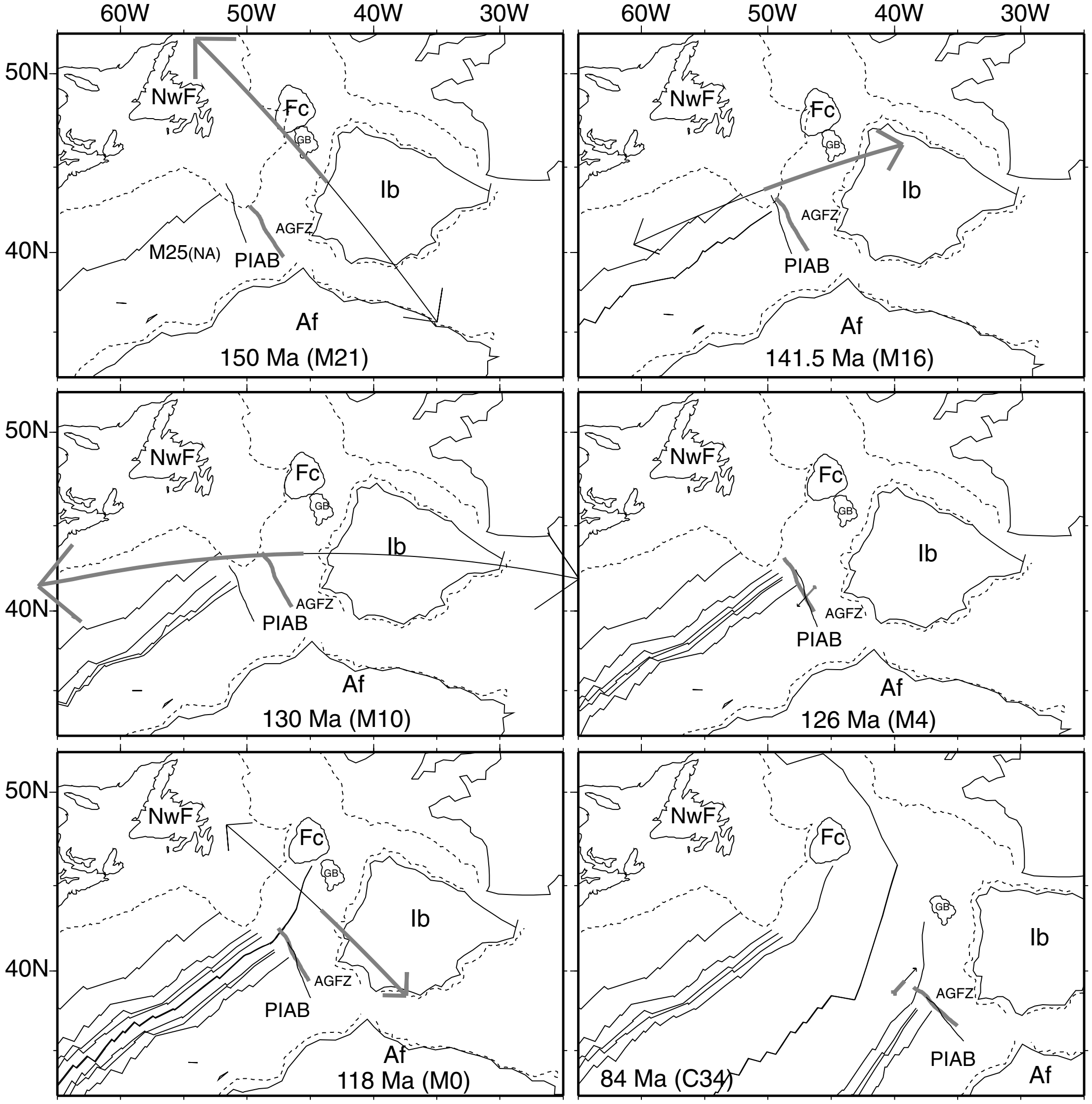

Figure 2. Plate tectonic maps. Reconstructions at: 150 Ma, anomaly M21 (only displayed anomaly M25 in North America); 141.5 Ma, anomaly M16; 130 Ma, anomaly M10; 126 Ma, anomaly M4; 118 Ma, anomaly M0; 84 Ma, Chron 34. Datum: geological timescale by Kent & Gradstein (1986). Fixed framework: North American Plate. Relative motion between Iberia (thick trace) and Africa (thin trace) is represented by arrows, their size is proportional to the relative velocity module (v) between the two plates: 150 Ma v = 38.061 mm yr^{-1}; 141.5 Ma v = 29.680 mm yr^{-1}; 130 Ma v = 71.292 mm yr^{-1}; 126 Ma v = 2.738 mm yr^{-1}; 118 Ma v = 25.703 mm yr^{-1}; 84 Ma v = 4.294 mm yr^{-1}. Also plotted is the trace of our inferred Late Jurassic–Early Cretaceous plate boundary between Iberia and Africa (PIAB). The thick trace is attached to Iberia, the thin trace is attached to Africa. The maps were produced with the plate kinematics software PLACA, developed by Matias *et al.* (in press), using the pole of rotations presented in Srivastava & Tapscott (1986), Olivet (1996), Srivastava *et al.* (1988) (Eurasia to North America, Iberia to North America); Klitgord & Schouten (1986) (Africa to North America); Olivet (1996), Srivastava *et al.* (1988), Argus *et al.* (1989) (Galicia Bank to North America); Olivet (1996) (Flemish Cap to North America). Digital ocean floor isochrons from Müller *et al.* (1997). Dashed lines shows the present-day 200-m bathymetry contour. Azores–Gibraltar Fracture Zone (AGFZ); Iberian Plate (Ib); African Plate (Af); Newfoundland (Nwf); Flemish Cap (Fc); Galicia Bank (GB).

summarized in Wilson *et al.* (2001). The margin has provided key points for the advance of the study of processes of continental rifting and exhumation of upper-mantle rocks and the better understanding of the continent–ocean transition (COT), a broad area located between thinned continental crust and normal oceanic crust. Unfortunately, the deep geophysical structure of the southern part of the margin is still puzzling. Only a small number of multichannel seismic reflection (MCS) profiles are available in the area and no modern refraction data have been collected yet. Along the northwest Iberia Atlantic margin the COT is located in a region 30–170-km wide, characterized by a very low or absent magnetic signature. The COT basement typically shows a two-layer structure: a thin upper layer of low velocity (3.5 to 5 km s^{-1}) characterized by a high gradient. In the layer below, velocities are in the range of 7.2–7.4 km s^{-1}, increasing with a gentle velocity gradient to normal mantle velocities of approximately 8.0 km s^{-1} (Whitmarsh *et al.* 2001). Three hypotheses have been proposed for the origin of the COT basement:

(i) thinned and intruded continental crust (Whitmarsh & Miles 1995; Whitmarsh & Sawyer 1996);

(ii) ultraslow (3–5 mm yr^{-1} half rate) seafloor spreading (Whitmarsh & Sawyer 1996) or slow seafloor spreading oceanic crust (Girardeau *et al.* 1998; Srivastava *et al.* 2000);

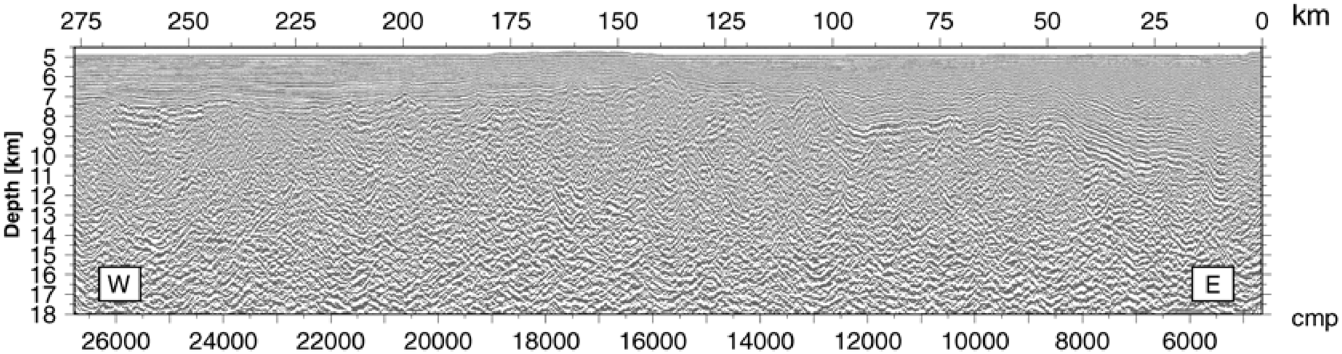

Figure 3. Marine magnetic anomalies from Verhoef *et al.* (1996) of the eastern Atlantic ocean offshore southwest Iberia and northwest African margins. Outlined seafloor topography from satellite altimetry (Smith & Sandwell 1997). Iberia Abyssal Plain (IAP); Tagus Abyssal Plain (TAP); Horseshoe Abyssal Plain (HAP); Gorringe Ridge (GR), Ampère Seamount (Amp), Coral Patch Seamount (CPS), Azores–Gibraltar Fracture Zone (AGFZ), Seine Abyssal Plain (SAP). Interpretation of the magnetic anomalies based on Roest *et al.* (1992) and Srivastava *et al.* (2000). Inferred Palaeo Iberia–Africa Plate Boundary (PIAB) during the opening of the Central Atlantic ocean. The boundary ends near M0, the youngest constrained anomaly.

(iii) serpentinized upper mantle exhumed during continental rifting by simple shear (Boillot *et al.* 1995) or pure shear (Brun & Beslier 1996; Pickup *et al.* 1996; Discovery 215 Working Group 1998; Chian *et al.* 1999; Dean *et al.* 2000).

Three legs of the ODP showed the widespread occurrence of serpentinized peridotites within the COT of the northwest Iberia margin, leading to the consideration of the acronym COT, at least for the case of the NW Iberian margin, as synonymous to a kind of crust consisting of exhumed and serpentinized upper-mantle rocks. Offshore Galicia a N–S oriented serpentinized lherzolitic ridge was drilled at ODP site 637 (Fig. 1; Boillot *et al.* 1987). ^{40}Ar/^{39}Ar dating of the syntectonic amphiboles showed an age of 122 ± 0.3 Myr (Boillot *et al.* 1989). Because synrift sediments are present only on the eastern flank of the ridge, its emplacement must have taken place during the last stage of rifting, before seafloor spreading started off Galicia Bank (GB in Fig. 1). To the south, in the Iberia Abyssal Plain, basement drilling recovered serpentinized peridotites over a broad region at ODP sites 897 and 899 during leg 149 (Sawyer *et al.* 1994) and at sites 1068 and 1070 during leg 173 (Whitmarsh *et al.* 1998). ^{40}Ar/^{39}Ar dating of the recovered metagabbros within the COT yielded an age of 136 Myr (Féraud *et al.* 1996). Peridotites may extend into the Tagus Abyssal Plain, where Pinheiro *et al.* (1992) found an anomalous thin crust, the absence of oceanic layer 3 and an upper-mantle material with velocities of 7.6–7.9 km s^{-1} (line 5 in Fig. 1), which is a seismic crustal structure comparable to the seismic model observed in the southern Iberia Abyssal Plain.

Further to the south, drilling of the Gorringe Ridge at DSDP site 120 (Ryan *et al.* 1973) recovered upper-mantle peridotite overlain by gabbros 143 Ma old (Féraud *et al.* 1986) and tholeiitic rocks. Whitmarsh *et al.* (1993) first hypothesized that the Gorringe Ridge is an uplifted fragment of the Iberian COT zone. Girardeau *et al.* (1998) observed that the peridotite–gabbro associations sampled from the Gorringe Ridge are very similar to those ones recovered within the COT off the NW Iberia margin, setting a comparison between the two domains. In contrast, Purdy (1975) proposed that the Gorringe Ridge is a slab of African oceanic crust overthrusted on the Eurasian Plate within a slow-consuming oceanic plate boundary scenario. The remainder of the African Plate, in his opinion, formed a northwest-dipping nascent subduction zone. The current phase of consumption might have started 10 Ma ago (Late Miocene). However, Sartori *et al.* (1994) and Hayward *et al.* (1999) found no evidence of an incipient subduction, they rather suggest that the Gorringe area is part of a wide zone of compressional deformation active for at least much of Tertiary age (the stippled-patch area in the insert of Fig. 1). Tortella *et al.* (1997) place the COT along line IAM3, near the crossing with line AR01 (Fig. 1), based on the interpretation of the MCS profiles. González *et al.* (1996) modelling near-vertical and wide-angle seismic data on line IAM3 (Fig. 1) found velocities of 5.8–6.0 km s^{-1} in the upper crust to ∼12-km depth and velocities of 7.8–7.9 km s^{-1} in the upper mantle, which are slightly lower than usual. They interpret the velocity structure as a transitional zone from the continental domain of the Gulf of Cadiz to the oceanic domain of the Gorringe Ridge area.

In this study we propose the location of the Palaeo Iberia–Africa Plate Boundary, (PIAB in Figs 2 and 3) active during the Late Jurassic–Early Cretaceous and we image the basement character across the Horseshoe Abyssal Plain, where we found the boundary between oceanic crust to the west and an eastern sector showing geophysical characteristics comparable to the COT areas of the NW Iberia margin.

2 SEISMIC PROCESSING OF LINE AR01

MCS line AR01 (Fig. 1) was acquired in 1992 within the framework of the Rifano project (Sartori *et al.* 1994), using an 80-L-airgun source and a 3-km-long, 120-channel, streamer. The shot interval was 50 m and record length 13 s. The total length of the line is 500 km, the westernmost 275 km have been reprocessed at Geomar Research Centre through time migration (Fig. 4) and pre-stack depth migration (Fig. 5). The starting point for pre-stack depth migration was chosen where the smooth seafloor topography gradient changes to a typical abyssal plain environment where the sea bottom is almost flat, below approximately 5000 m of water depth. The processing included trace editing, amplitude balancing, normal move-out correction, common-midpoint stacking, predictive deconvolution, finite-difference time migration and time variant band-pass filtering. We iteratively pre-stack depth migrated the line to 18 km in depth with depth focusing error analysis every 200 CMPs to create the velocity model, shown in Fig. 6.

3 MAGNETIC ANOMALIES

Off GB (Figs 1 and 2) no seafloor spreading magnetic anomalies have been observed: the first oceanic crust probably formed

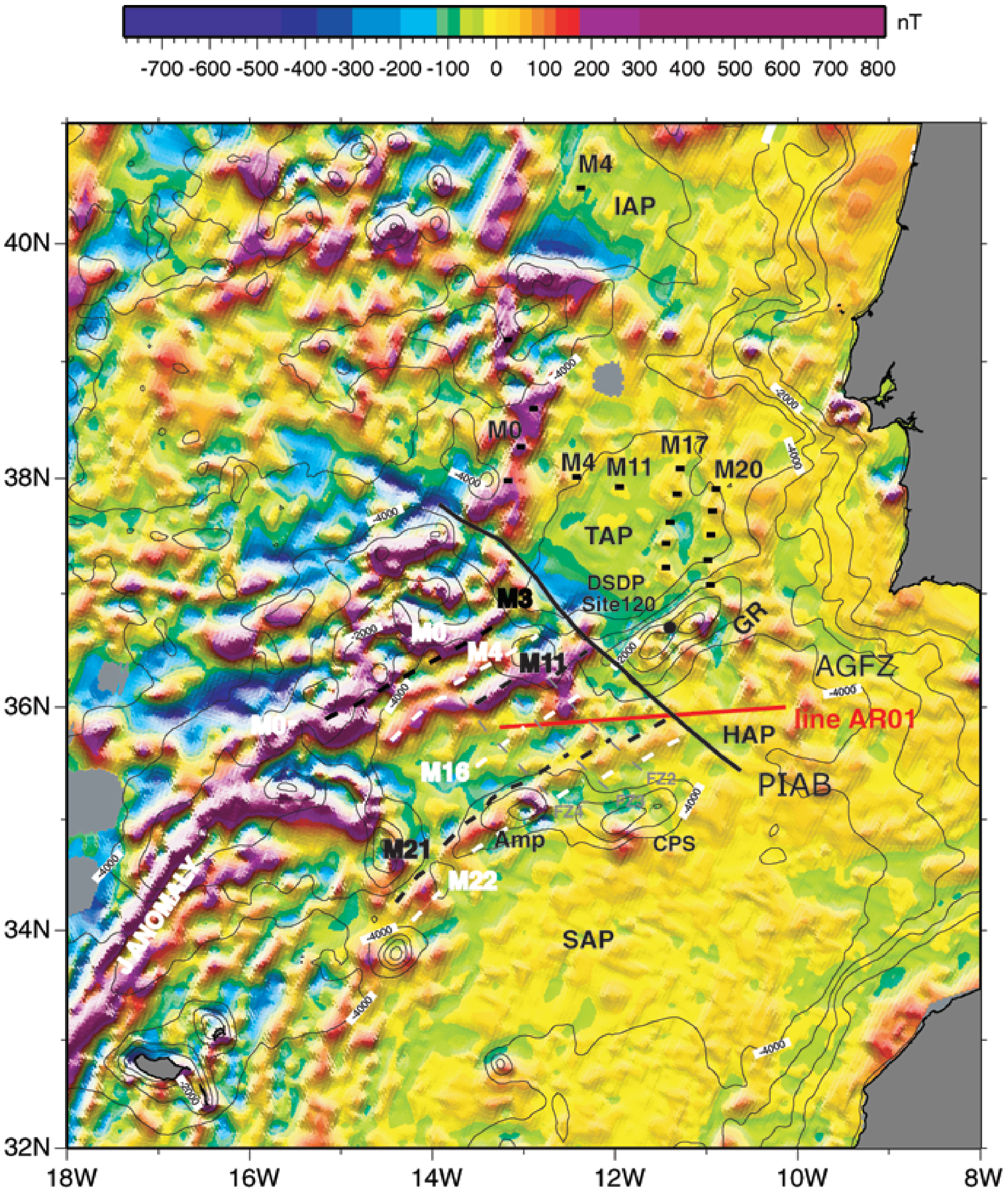

Figure 4. Finite differences time migration of line AR01, vertical exaggeration of 5. Magnified portion shows the sedimentary sequence and the seismostratigraphic units of the western Horseshoe Abyssal Plain, as termed in Hayward *et al.* (1999).

during the Cretaceous magnetic quiet interval or, as hypothesized by Boillot & Froitzheim (2001), the area represents a zone of serpentinitic seafloor; both processes do not give rise to significant magnetic anomalies. In the southern Iberia Abyssal Plain, M3 (124 Ma) is the earliest seafloor spreading magnetic anomaly (Whitmarsh *et al.* 1990; Whitmarsh & Miles 1995). In Fig. 3, instead of M3, we have depicted anomaly M4, because in this compilation it is more visible. Pinheiro *et al.* (1992) interpret anomaly M11 (133 Ma) as the initiation of seafloor spreading in the Tagus Abyssal Plain (Fig. 3). Srivastava *et al.* (2000) agree with the interpretation of M3 as the oldest magnetic anomaly in the Iberia Abyssal Plain, but they do not rule out the presence of older anomalies, probably M10–M11, immediately to the south and M17–M20 in the Tagus Abyssal Plain (Fig. 3). Further to the south, offshore the SW Iberia margin within our study area (AGFZ in Fig. 3), the amplitude of magnetic anomalies is low and no magnetic lineations have been mapped. We used the compilation of Verhoef *et al.* (1996) and the magnetic lineaments interpreted by Srivastava *et al.* (2000) to locate the magnetic boundaries in relation to the basement features in line AR01 (Fig. 3). Weak features in the Tagus Abyssal Plain might be interpreted as anomalies M17 and M20 striking continuously from Tagus Plain towards Gorringe Ridge. In agreement, DSDP site 120, located slightly westward of M17 (144 Ma), yielded an age of 143 Myr for the oceanic crust gabbros (Féraud *et al.* 1986). In the

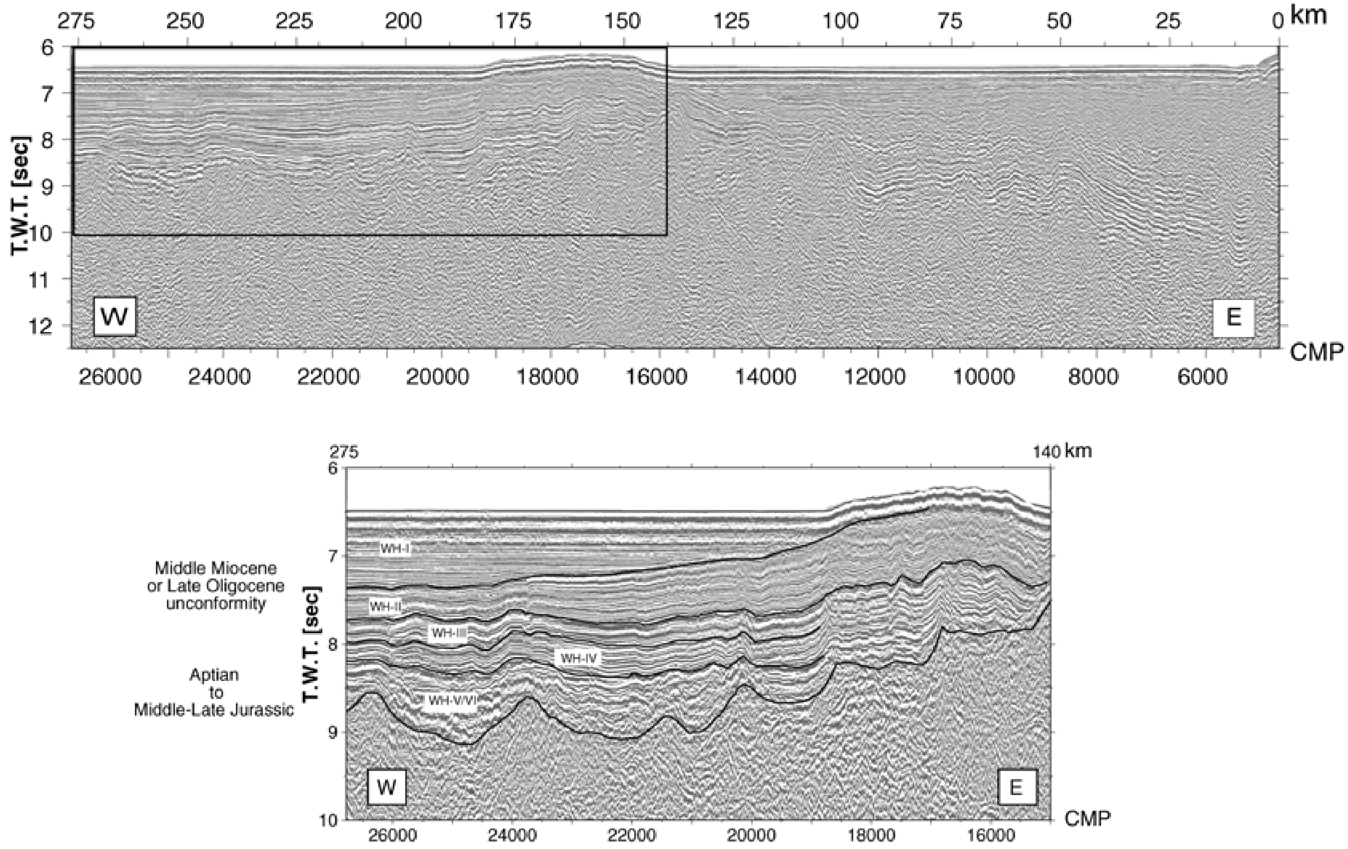

Figure 5. Pre-stack depth migration of line AR01, vertical exaggeration of 5.

eastern Horseshoe Abyssal Plain, magnetic anomalies do not define continuous lineaments, but we identify a series of local maxima that unlikely represent seafloor spreading anomalies. Local maxima may be related to topographic highs, outcrops of the basement, fault-bounded blocks of thinned continental crust or thrust-related shallowing of a giant chaotic body, discharged from the accretionary prism off the Straits of Gibraltar, as revealed by the two MCS lines presented in Figs 7(a) and (b). A sharp boundary in magnetic signature occurs across a NW–SE trending alignment, here termed PIAB (Fig. 3). South of PIAB, fairly continuous magnetic lineaments striking SW define the M-series formed by seafloor spreading of the Central Atlantic ocean. We have extended northwards the interpretation of Roest *et al.* (1992) in the Canary Basin to identify magnetic anomalies of the M-series and several small-offset fracture zones that do not cross line AR01, named FZ2, FZ3 and FZ4 in Fig. 3.

Therefore, north of PIAB most magnetic lineaments are not well defined, but M0 is probably the oldest lineament that can be followed with confidence together with the J anomaly, of which it represents the younger end (Srivastava *et al.* 2000). Northwards the M0-J anomaly seems to strike at a different angle from the M-series defined in the African Plate, following this interpretation we have stopped the M-series of the African crust along our PIAB lineament. The western segment of line AR01 runs across ocean crust of the M-series of the African Plate ranging in age from approximately M21 (150 Ma) to M16 (141.5 Ma). In contrast, the segment of AR01 east of PIAB is located in the area southeast of any of the magnetic features tentatively mapped in the Tagus Abyssal Plain (M17, M20) and thus in lithosphere of unknown nature. This lithosphere, in our interpretation, should be formed during the evolution of the continental rifting of the Iberian margin but, as its nature is undefined, we only can say that it is located west of the seismically defined continental crust of the SW Iberia margin, based on the works of González *et al.* (1996) and Gràcia *et al.* (2003) and it may be addressed as a COT zone. In Fig. 2, we have inserted the trace of the two segments of the PIAB within the plate kinematics reconstructions back to 150 Ma ago at anomaly M21. The pictures briefly show the history of this boundary, which faced strong tectonic activity within the area known in literature as the AGFZ.

4 VELOCITY DISTRIBUTION IN THE HORSESHOE PLAIN

We pre-stack depth migrated the data of line AR01 in order to obtain the correct geometry of the crustal structure distorted in the time section by lateral and vertical changes in velocity. The macrovelocity model used for pre-stack depth migration was obtained by interactive and simultaneous visualization and picking of common reflection point gathers and focusing analyses (MacKay & Abma 1992). The upper 1–3-km layer of the basement shows a velocity of 4.5–5.0 km s^{-1} with a high gradient. Beneath, a 4–5-km thick layer has a velocity increasing from 5.0 to 6.0–6.2 km s^{-1} with a low velocity gradient (Fig. 6). Velocities higher than 5.0 km s^{-1} are beyond the resolution of our data and we simply increased them with depth, following the trend. Depth-focusing analysis and common reflection point gathers indicate that the depth error is less than 100 m for the sedimentary sequence and less than 300 m for top basement.

Published refraction data in the area provide a few constraints for our velocity model (Purdy 1975). Line D overlaps the western end of profile AR01 and line B and its reverse BR are

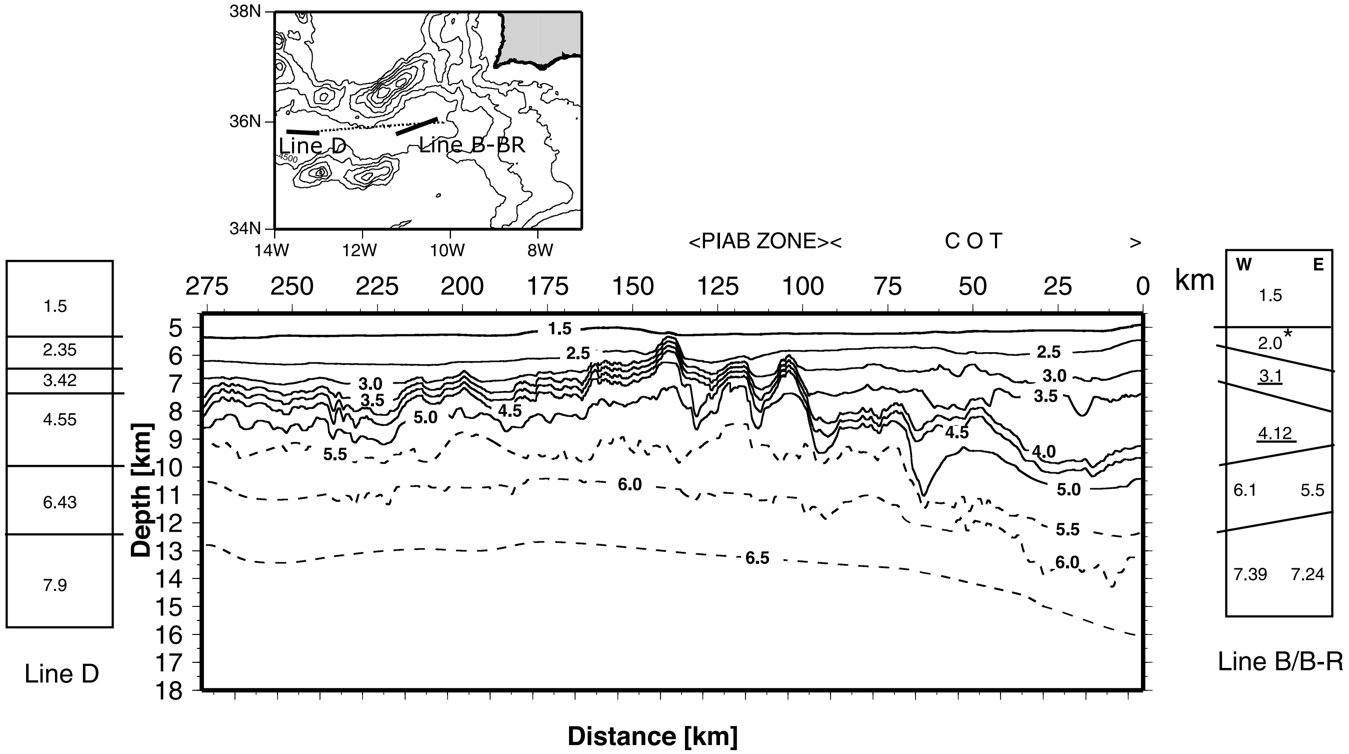

Figure 6. Pre-stack depth migration velocity model of line AR01, velocities are in km s^{-1}. Also shown, velocity information from Purdy (1975). In lines D and B/BR all velocities are apparent, except underlined values that indicate velocities corrected for refraction dip. The values with an asterisk indicate assumed velocities.

located right across the eastern sector of line AR01 (Figs 1 and 6). Purdy (1975) modelled the depth of the Moho in the western Horseshoe Abyssal Plain at 10–12 km below sea level; line D yields a typical oceanic crustal section, with crustal velocities of 6.2 km s^{-1} changing abruptly to upper-mantle velocities of nearly 8.0 km s^{-1}. In contrast, Purdy (1975) found on lines B and BR, at the eastern end of line AR01, an oceanic crustal thickness, but an anomalous velocity structure. Upper-mantle velocities beneath the eastern Horseshoe Abyssal Plain are lower than usual (7.2–7.4 km s^{-1}), similar to velocities observed for layer 2 within the COT of the west Iberia margin.

We performed arrival time modelling and inversion for lines B and BR, using ray tracing in a 2-D model by asymptotic ray theory with the software developed by Zelt & Smith (1992). Each 0.5-km s^{-1} velocity contour derived from our model was converted into a Zelt & Smith (1992) model layer. We modified our velocity model below the 5.0-km s^{-1} contour adding a layer for the *Pn*-phase, upper-mantle arrivals, estimated to be 7.4 km s^{-1}. We digitized the time–distance curves for lines B and its reverse BR (21 data points for shot B and 44 data points for shot BR) available in Purdy (1975), displayed as insets in Figs 8(b) and (d). Fig. 8 shows the results of the ray tracing, where there is a good fit between the observed travel times (represented by the vertical bars) and the computed travel times (represented by the solid lines). Sediments are well modelled, but there is a misfit at shot B where some first arrivals from the basement are absent. This can be the result of several problems inside our model: the basement is overwhelmed by a huge chaotic mass and lateral changes in the model are not well supported by the pre-stack depth migration technique.

The velocity model used for the pre-stack depth migration is shown to be consistent with wide-angle and refraction results, but it is not reliable for layers with velocities higher than 5.0 km s^{-1}.

5 DESCRIPTION OF LINE AR01

The processed part of line AR01 can be divided into three sectors, the eastern one between 0 and 80 km (Fig. 9a), the central sector from 80 to 155 km (Fig. 9b) and the western sector from 155 to 275 km (Fig. 9c). The basement is poorly imaged in the easternmost segment (Fig. 9a) because of a giant chaotic body emplaced during the Miocene (Torelli *et al.* 1997). The oldest sediments recovered in this area at DSDP site 135 (Hayes *et al.* 1972) are Early Aptian (119 Ma) in age, but drilling, undertaken on a topographic high located 35 km away from the southeastern termination of the plain, stopped at ~1 km from top basement. Turbidites above the chaotic body show relatively little deformation, with the exception of some small thrust faults and folds (Zitellini *et al.* 2004).

In the central sector, the basement shows several large highs that locally reach a relief higher than 2 km and seem to be related to straight eastward-dipping reflections. A poorly imaged eastward-dipping reflection is present at approximately 100 km (L1 in Fig. 9b). The dipping reflections at approximately 110 km and at 130 km (L2 and L3 in Fig. 9b) are well displayed across much of the basement, but are poorly imaged in the upper portion, however they seem to project to an offset at the top. The dipping reflections transect from near top basement to later than 11 s two-way travel time (TWT) in the time section (Fig. 4) and reach 13–15 km in the depth section (Fig. 5). L3 is also shown in Fig.10 and seems to project to an offset in basement topography. The

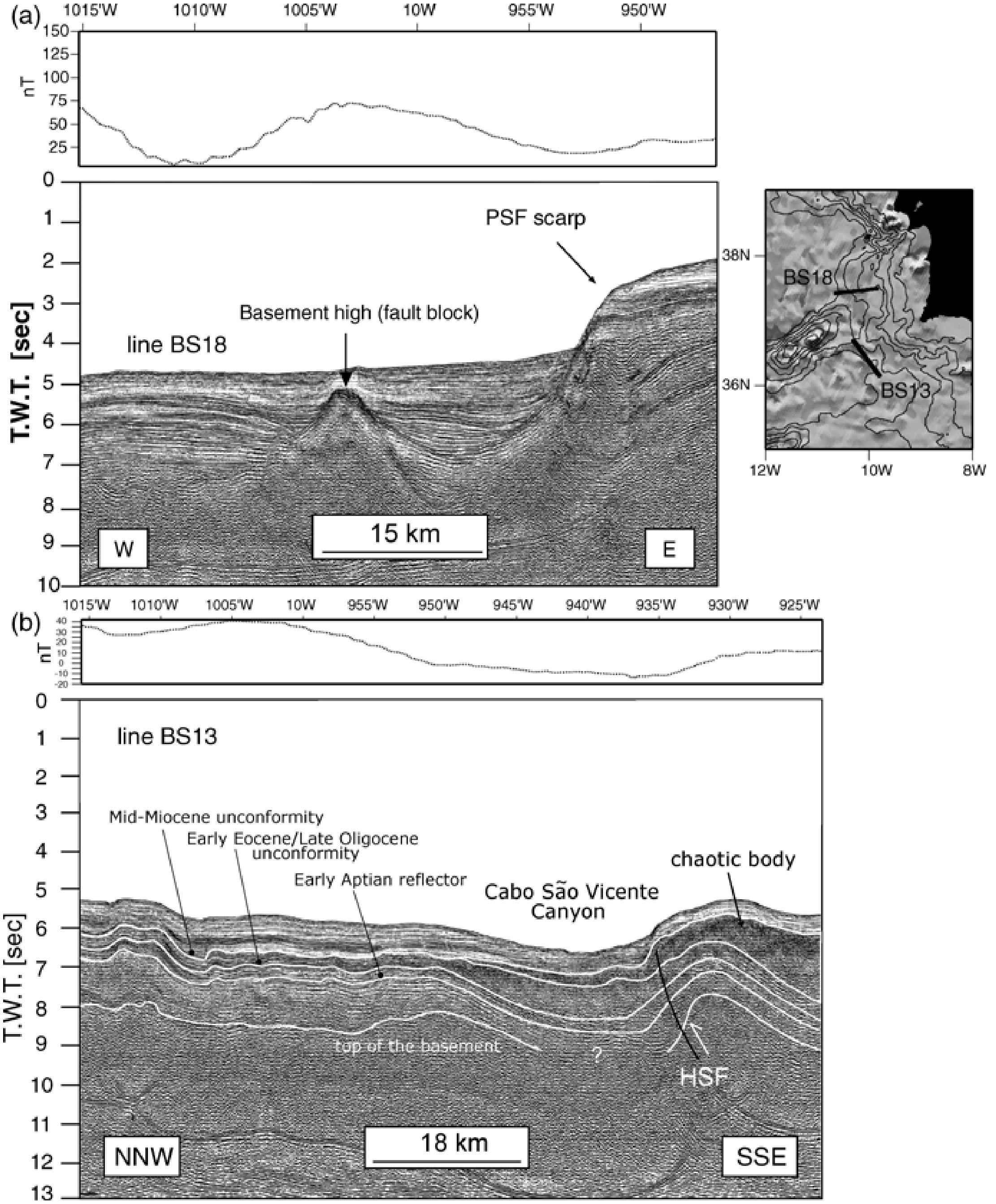

Figure 7. Time migration of MCS lines BS18 (a) and BS13 (b). The magnetic profiles above the two lines show the high-amplitude anomalies in respect to the geological features. Line BS18 has been acquired across the Pereira de Sousa scarp (named by Terrinha *et al.* 2003) and shows a shallow basement block, probably inherited from the structure of the margin during continental rifting. Line BS13 shows the shallowing of the giant chaotic body where the Horseshoe Fault (HSF) (named by Zitellini *et al.* 2001) breaches the seafloor. Stratigraphic information is provided by regional seismostratigraphy correlation performed over the whole area, based on DSDP sites 120 (Ryan *et al.* 1973) and 135 (Hayes *et al.* 1972).

deepest sediments lying on the flanks of the basement highs show a clear tilting indicating that they were deposited before or during extensional faulting. In the intervening basement lows, gently tilted sedimentary in-filling suggests a syntectonic deposition, especially on top of L3 (Fig. 10), while on top of L2 the plane-parallel bedding suggests a post-tectonic deposition. Sediment overlying the highs is little tectonized and only the westernmost of the basement highs shows relevant deformation in the overlying sediments. This compressional pattern may be the result of recent deformation. It is probably related to uplift at the southwestern tip of the Gorringe Ridge, which might have occurred in Miocene, possibly at Tortonian times (8 Ma) (Mauffret *et al.* 1989).

West of 155 km, the basement relief becomes smoother, although landward-dipping reflections are still visible cutting deep into the basement (L4 and L5 in Fig. 9c). Continuous, low-frequency westward-dipping reflections cut across much of the basement (S1, S2, S3 in Fig. 9c). A sub-horizontal reflection is also visible between 230 and 275 km at a depth of ~6 km beneath top basement. Similar

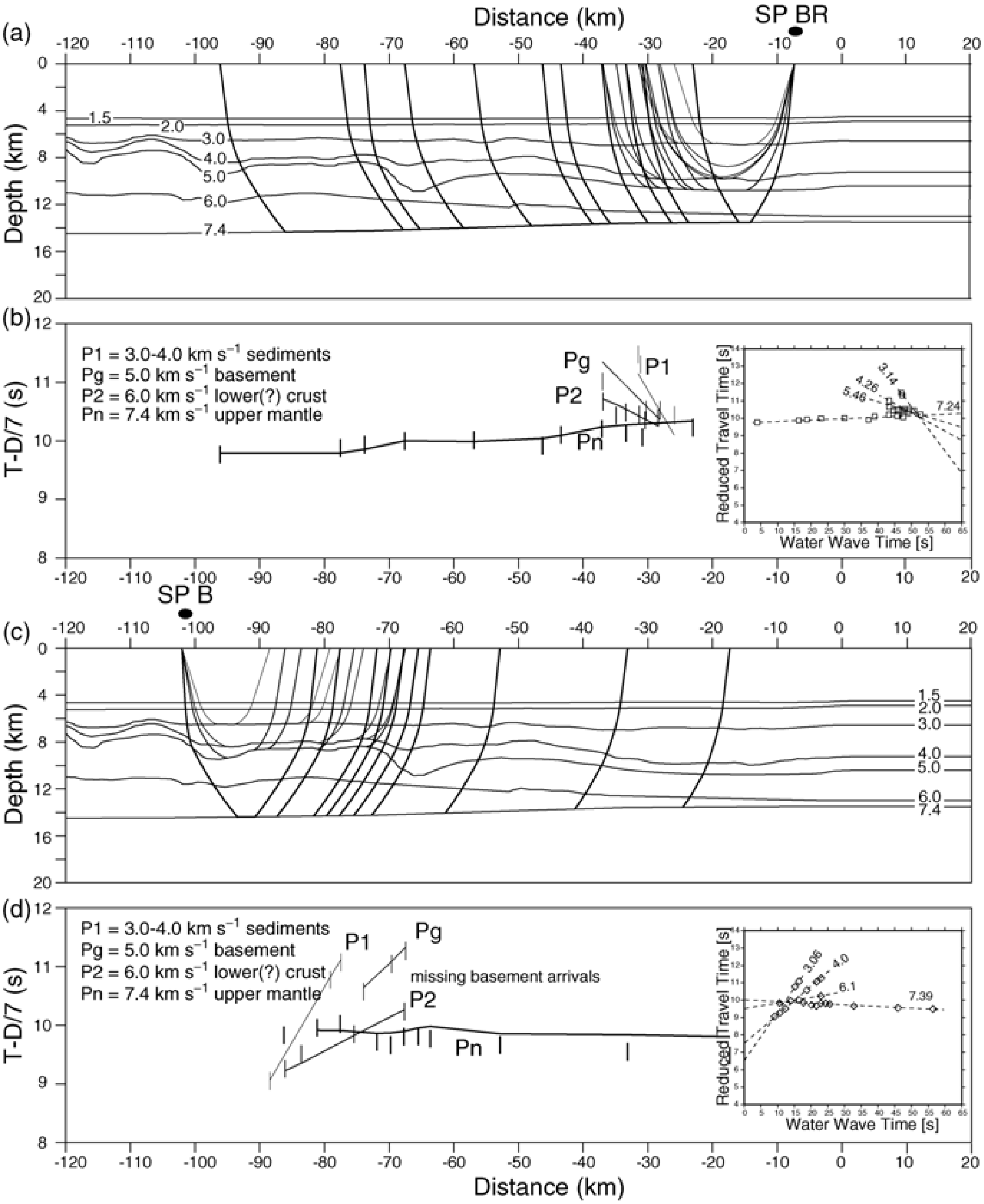

Figure 8. Ray path diagram (a) and traveltime comparison (b) for our velocity model applied to sonobuoy B. Ray path diagram (c) and traveltime comparison (d) for our velocity model applied to shot BR. Our velocity model underlies the ray tracing path in (a) and (c), velocities are km s^{-1}. Vertical bars in (b) and (d) show the observed traveltimes, their heights are equal to twice the estimated *a priori* error (0.15 s). Continuous lines in (b) and (d) are the computed traveltimes from the model. Inserts in (b) and (d) show the original Purdy's time–distance plots for seismic refraction lines. Reducing velocities of 7 km s^{-1}, after Purdy (1975).

reflections have been described elsewhere in Central Atlantic ocean crust and interpreted as oceanic Moho (e.g. Ranero *et al.* 1997). The sedimentary sequence shows a deep unit, named WH-V/VI by Hayward *et al.* (1999) (Fig. 4), which might be Late Jurassic to Early Aptian in age, i.e. the first stage of seafloor spreading in the Central Atlantic ocean. In the upper sediments there is a prominent angular unconformity, separating WH-I from WH-II in Fig. 4. The shallow deformation in the sediment layer and this unconformity might be related to the end of the Late Oligocene/Late Miocene compressional event in the area, which caused the emplacement of the accretionary prism, the discharge of the giant chaotic body and the uplift of the Gorringe Ridge.

6 INTERPRETATION OF THE SEISMIC IMAGES AND DISCUSSION

The eastern part of line AR01, east of the PIAB, is characterized by thinned, deep and low relief basement and no fault block

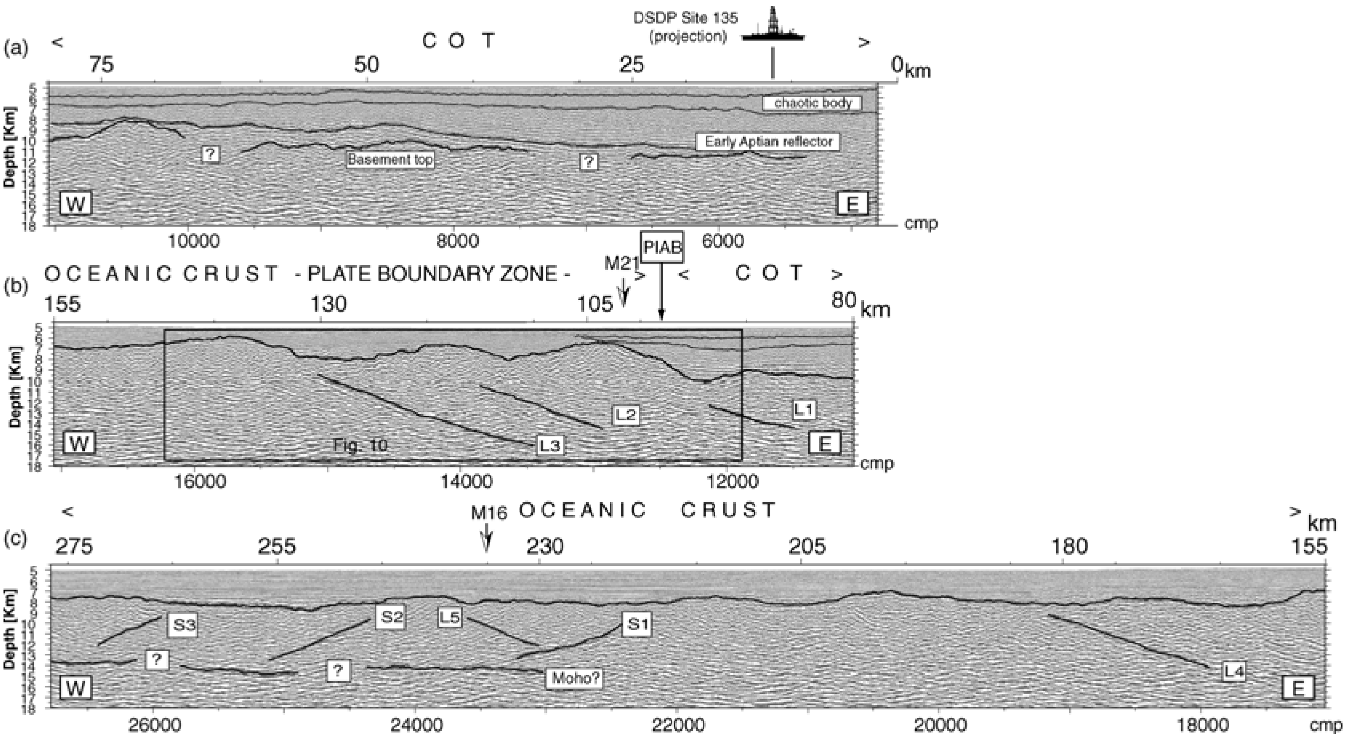

Figure 9. Line drawing of line AR01 with no vertical exaggeration: (a) shows the eastern sector of the line from 0 to 80 km; (b) shows the central sector between 80 and 155 km; (c) shows the western sector west of 155 km. See text for discussion. Framed box outlines the content of Fig. 10. Probable Palaeo Iberia–Africa plate Boundary (PIAB) during the opening of the Central Atlantic ocean. Projections of M anomalies are also indicated.

structure can be observed, although we must stress that the substratum character is not well imaged beneath the giant chaotic body. The lithosphere, as suggested by González *et al.* (1996), shows continuous thinning from the continent to the oceanic domain.

In the absence of a velocity model of the area offshore the SW Iberian Peninsula well-constrained with modern data, we use the combination of several other observations to reinforce our interpretation.

(i) No detectable seafloor spreading anomalies, similar to the COT along other areas of west Iberia, perhaps indicates a serpentinitic basement in the eastern Horseshoe Abyssal Plain.

(ii) Limited wide-angle and refraction data (Purdy 1975; González *et al.* 1996) suggest a transitional character for the area between continental and oceanic crust.

(iii) The tectonic structure enlightened by the seismic records of the first sector of line AR01 is different from the typical fault blocks of thinned continental crust, imaged along the W Iberia margin [e.g. eastern end of line IAM9 in Pickup *et al.* (1996); eastern end of line IAM5 in Afilhado *et al.* (1999)] or along the Algarve margin (Terrinha 1998).

(iv) MCS line AR09 (Fig. 11), located north of line AR01, runs from the eastern flank of the Gorringe Ridge to the Ormonde Seamount and displays fault-bounded blocks landward of the basement consisting of serpentinized peridotites, intruded by gabbroic sills (Girardeau *et al.* 1998). Line AR09 images thinned continental crust along the eastern flank of Gorringe, which may indicate that progressive stretching of the continental lithosphere led to mantle exhumation at the top of the seamount along a low-angle normal fault, according to lithosphere necking models proposed for the Iberian margin (Brun & Beslier 1996) and the observations of Girardeau *et al.* (1998). The interpreted extent of the COT along the W Iberia margin (Fig. 12), east of PIAB, suggests that it is part of the swath of anomalous lithosphere located west of the thinned continental crust.

(v) In favour of an analogy with other COT areas, we observe also the very low relief of the basement in the eastern sector of line AR01 compared to the plate boundary zone, which shows large-scale basement topography, similar to the transition observed in line 85-2 offshore Newfoundland (Fig. 13b; Keen & de Voogd 1988; Reid 1994), line IAM9 in the southern Iberia Abyssal Plain (Fig. 13c; Pickup *et al.* 1996) and line Norgasis 14 in the Armorican Basin (Fig. 13d; Thinon *et al.* 2003). In these areas, wide-angle seismic data show high velocities (7.2–7.4 km s^{-1}) for the low-relief basement zone, interpreted as partially serpentinized upper-mantle rocks.

Whatever the nature of the basement rocks may be, we argue that the COT area of line AR01 is mostly comparable to the other transitional areas of the N and NW Iberian margins.

The central sector of line AR01, here referred as the plate boundary zone, is characterized by a relevant relief, elevated up to >3 km above the adjacent crust. The uneven basement topography is associated with the presence of deep and straight landward-dipping reflections. Although magnetic anomaly M21 runs across the area, the seismic images do not display typical characteristics of oceanic crust, but the region seems to lie too far from the continent to be ascribed to a geometry of fault-bounded blocks of thinned continental crust. The basement topography shows highs in the central sector as large as inside-corner highs of slow spreading centres. The inside corners are areas of thick lithosphere where extensional tectonics lead to the exposure of mantle rocks through large-scale

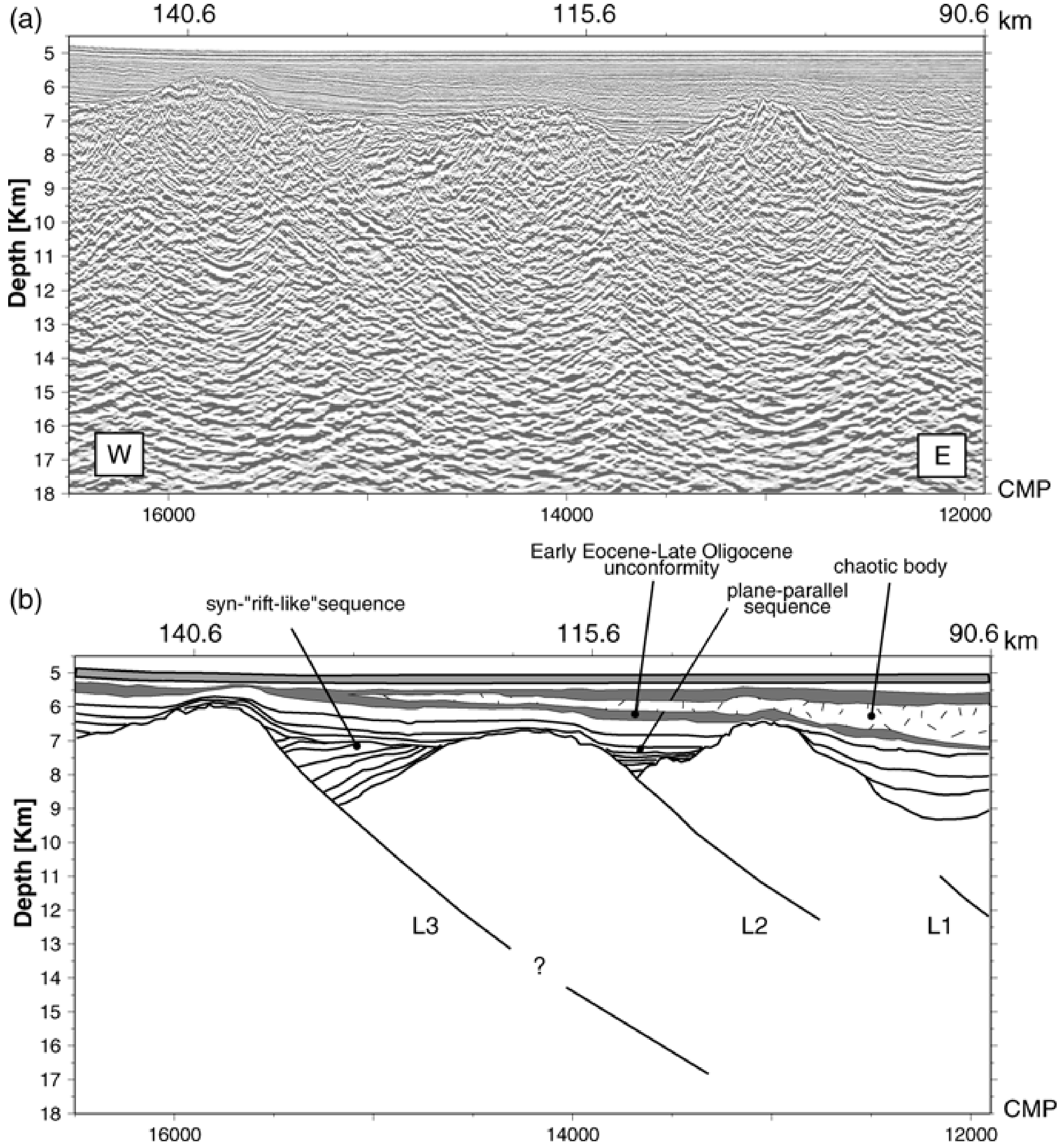

Figure 10. Plate boundary zone of line AR01. (a) Portion of the seismic line AR01, framed in Fig. 9(b), (b) line drawing showing the landward-dipping reflectors L1, L2, L3 and the intervening syntectonic sequence on top of L3 and the plane-parallel geometry of the sediments on top of L2.

faulting. Fault related topography at inside corners typically shows a 1.2–2.0 km (Tucholke *et al.* 1998), 0.5–1.5 km (Ranero & Reston 1999) topographic relief and 2 km or higher at the Gakkel Ridge (Coakley & Cochran 1998). The largest relief of the Gakkel Ridge walls, comparable to the structure observed in the central sector of line AR01, appears where the spreading centre ends abruptly against a broad zone of diffuse continental rifting (Coakley & Cochran 1998). At ocean core complexes, seismic images (Ranero & Reston 1999) do not show major tilting in the intervening sedimentary sequence. In contrast, in line AR01 the sedimentary sequence appears to be tilted on top of L3 and the sedimentary wedge thickens towards the footwall, suggesting a syntectonic deposition, that we termed a synrift-like sequence in Fig. 10. Furthermore in line AR01 the extensional tectonics exhibit long-lasting activity in time, because the sedimentary in-filling seem to be thick consistently with the rifting history of this area, while detachment faulting at ocean core complexes shows a short-lasting activity averaging 1 Ma (Tucholke *et al.* 1998).

The central sector of line AR01 probably represents a relict segment of the transform plate boundary separating the Central Atlantic spreading and the Iberian continental rifting. Although our seismic images do not show clear evidence of strike-slip faults, L3 might represent the trace of faults from a leaky transform responsible for crustal stretching along the fossil plate boundary during the interval M21–M16. The relative motion between Iberia and Africa (Fig. 2) suggests a transtensional component along the plate boundary between M21 and M10, with a higher relative velocity between the two plates (in the range of 4–7 cm yr^{-1}). After M10, the movement may have changed to transpression and subsequently to an almost N–S directed compression, characterized by a very low velocity module (0.4 cm yr^{-1}), in slight disagreement with the hypothesis of Iberia attached to Africa immediately before Chron 34 (Srivastava *et al.*

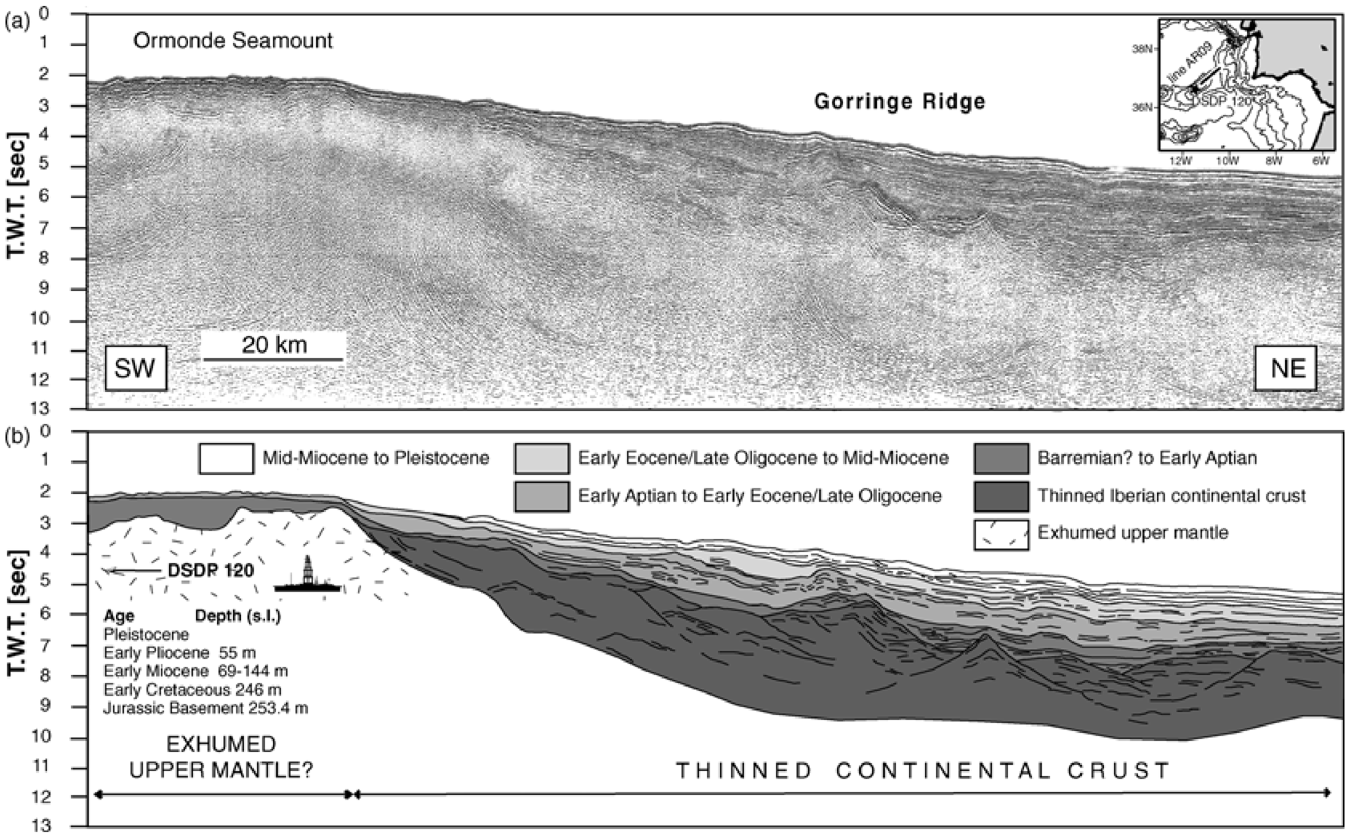

Figure 11. Time migration of line AR09, shot on the eastern flank of Gorringe Ridge, showing the continental crust, organized in fault bounded blocks and the lithosphere at the Ormonde Seamount, in the vicinity of DSDP site 120, where peridotites overlain by gabbros have been sampled. According to Girardeau *et al.* (1998) the Gorringe Ridge lithosphere formed by passive tectonic denudation of the mantle. Given stratigraphic information is based on regional correlation made over the whole area, based on DSDP sites 120 and 135.

1990a,b; Roest & Srivastava 1991), even though we used the same poles of rotation.

The segment of line AR01 west of 120 km, westwards of the plate boundary zone, is characterized by a low relief at the top basement, westward-dipping reflectors and a probable oceanic Moho reflection, appearing towards the western end of the profile. Refraction seismic data (line D) modelled by Purdy (1975) indicate an oceanic nature for the basement of the western Horseshoe Abyssal Plain. In agreement, clear seafloor-spreading magnetic lineaments intersect the line and fade towards the PIAB. The crust west of 120 km in line AR01 formed at a half spreading rate of 10 to 19 mm yr^{-1} (Klitgord & Schouten 1986), between anomalies M21 and M16. The half rate calculated for the oceanic crust of the southern Iberia Abyssal Plain by Whitmarsh & Miles (1995) is ~10 mm yr^{-1}, which may explain the slightly larger relief found there, in respect to the smooth basement topography in the images of the Horseshoe Abyssal Plain. A gradual increase in top basement roughness has been found to be associated with constant decrease in the spreading rate (e.g. Canary Basin, Ranero *et al.* 1997).

7 CONCLUSIONS

Interpretation of magnetic data available in the study area suggests that the seismic reflection line AR01 runs across the palaeo plate boundary between Africa and Iberia during the opening of the Central Atlantic ocean (PIAB) separating two domains.

To the west of PIAB, Late Jurassic to Early Cretaceous (M21 to M16) oceanic crust formed by seafloor spreading between Africa and North America during the opening of the Central Atlantic ocean.

To the east of PIAB, occurs basement with no clear seafloor spreading magnetic anomalies and no clear fault-bounded blocks. Velocity information, obtained by the pre-stack depth migration of line AR01, is consistent with the refraction and wide-angle data available in the area. This information, although limited, suggests that the seismic velocities computed by the depth-focusing analysis fall in the range of values generally described for the transitional zone off the northwest Iberian margin and supports that this area is the COT of SW Iberia. It is unclear whether the eastern sector of the line belongs to the southern margin of the Iberian Peninsula, related to the neo-Tethys system, or whether it belongs to the western Iberian domain and formed soon before the opening of the North Atlantic ocean.

The plate boundary zone lies between oceanic crust of the Central Atlantic and an area that we defined as transitional. It is expressed as large-scale fault-bounded crustal blocks associated with deep-penetrating landward-dipping reflections and long-lasting tectonic activity, testified by fanning sediments on top of the largest reflector. The nature of the crust there is unknown, although seafloor spreading anomaly M21 projects to them. We interpret that this sector behaved as a leaky transform plate boundary, separating Central Atlantic ocean crust from the Iberian continental rifting, during the interval M21–M16.

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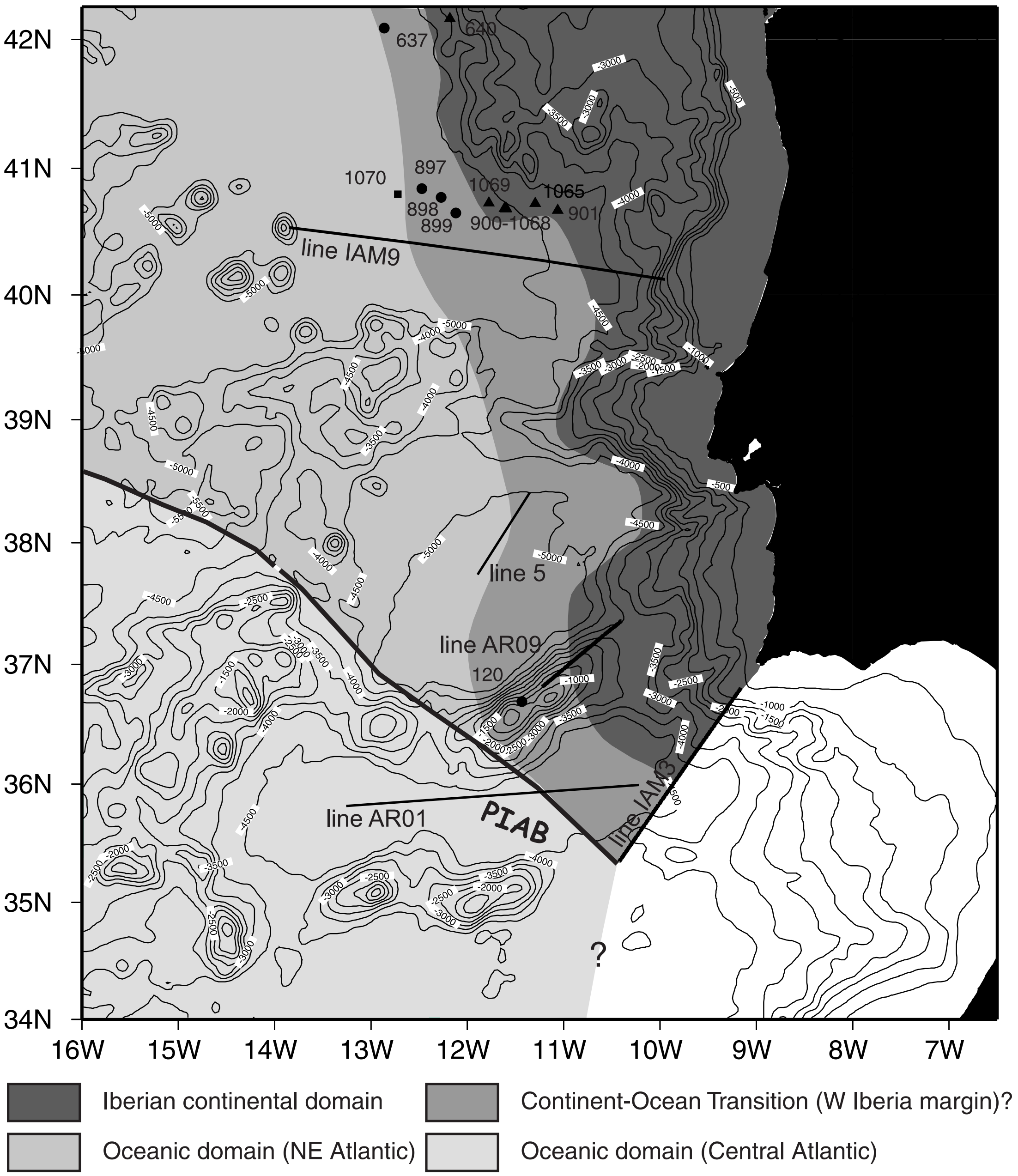

Figure 12. Sketch of the COT extent along the W Iberia margin, based on this work and the compilation of information from previous work quoted through the text. The COT in the Horseshoe Abyssal Plain is offset eastward of the COT along Tagus and Iberia abyssal plains, consistently with the model of northward rift propagation predicted for the margin (Beslier *et al.* 1993).

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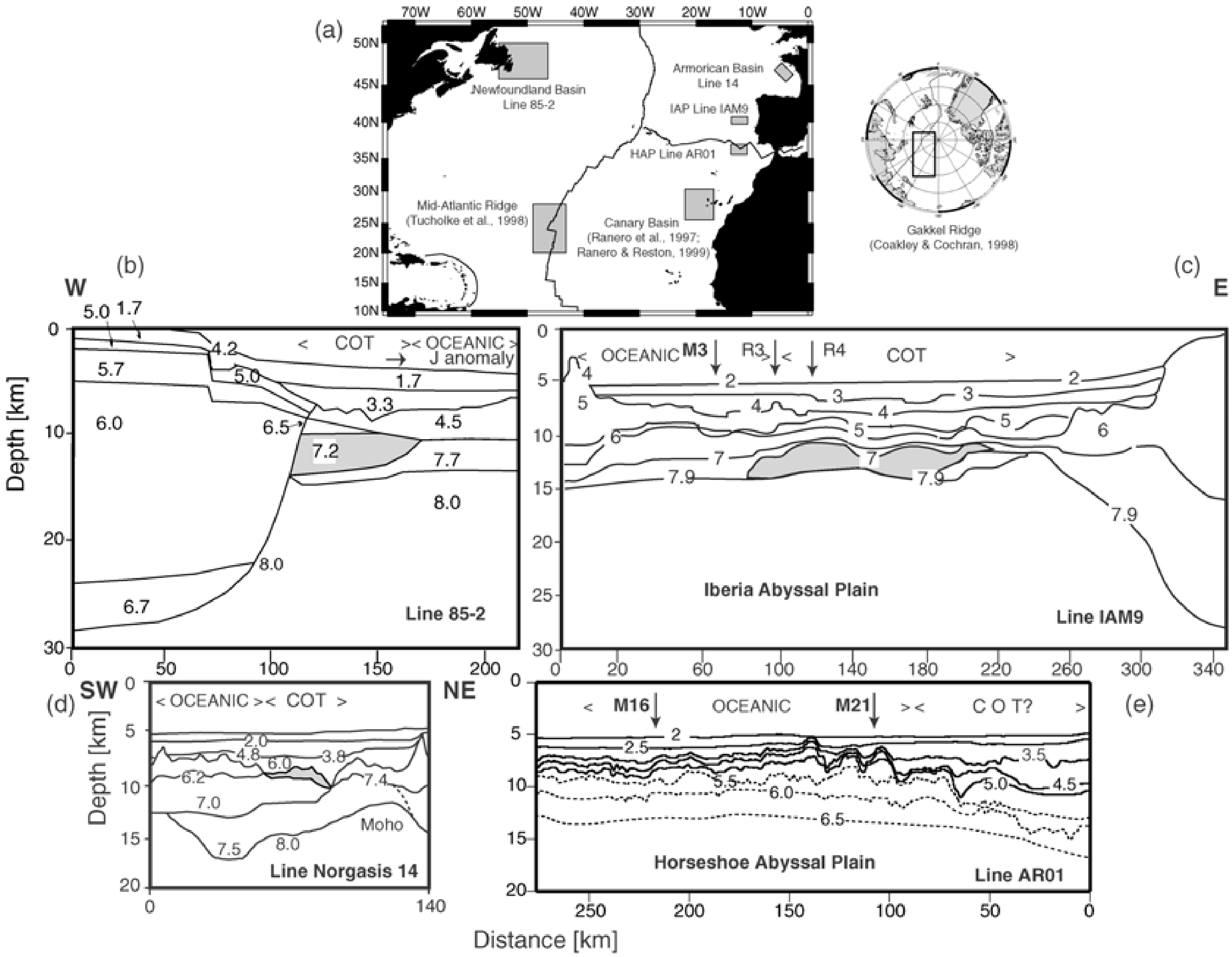

Figure 13. (a) General map of the Atlantic Ocean with locations of the ocean and transitional crust examples discussed in the text. Present-day plate boundaries taken from Fig. 1; (b) velocity model of line 85–2 modified after Reid (1994); (c) velocity model of line IAM9, modified after Dean *et al.* (2000); (d) velocity model of line Norgasis 14, modified after Thinon *et al.* (2003); (e) velocity model of line AR01. Velocity/depth profiles are at the same vertical and horizontal scales, with grey filling showing material with velocities in the range of 7.2–7.4 km s^{-1}.

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